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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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TECHNICAL NOTE

No. 1258

EXPERIMENTAL VERIFICATION OF TWO METHODS FOR COMPUTING THE TAKE-OFF GROUND RUN OF PROPELLER-DRIVEN AIRCRAFT

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SUMMARY

A comparison is presented between the measured take-off ground run of an airplane equipped with seven different propeller-engine gear-ratio combinations and the computed distances by two different methods.

In the more simple method (NACA Rep. no. 450, 1932, entitled "The Calculation of Take-Off Run" by Walter S. Diehl) the assumption was made that the net thrust, that is, accelerating force, varies linearly with airspeed. In the more refined method a point-by-point computation was made of the net accelerating force from instantaneous values of ground friction, thrust, drag, and lift. (The latter two quantities were determined with the aid of wind-tunnel tests that included the effects of the slipstream in the presence of the ground.) An estimation of propeller thrust for both methods was made by the use of NACA ARR No. 3G26, 1943 entitled "Working Charts for the Computation of Propeller Thrust Throughout the Take-Off Range" by Desmond and Freitag.

In the majority of cases, values of ground run calculated by Diehl's approximate method checked experimental values within ±7 percent but were in error as much as 15 percent in the case of a propeller which was operating at an unfavorable power loading. Attempts to improve the accuracy of the ground-run calculation by use of the refined method did not appear warranted unless strictly applicable thrust data or an improved method of thrust computation to avoid large errors in unusual cases are available. Even in the case of highly loaded propellers the effects of slipstream on drag are of secondary importance, and furthermore are in such a direction as to cause the accelerating force to approach more closely the linear variation assumed by Diehl.

INTRODUCTION

With the increased power of modern military aircraft causing a trend to more highly loaded propellers there is reason to examine conventional methods of computing take-off run which were based on assumptions which have been verified under less extreme conditions. For example, the widely used method of Diehl (reference 1) is based on the assumption that the net thrust, that is, accelerating force, decreases with an increase in airspeed in a linear fashion. Usage indicated this assumption to be reasonably correct for propellers of normal section and blade width, at thrust loadings (and accompanying slipstream velocities) of 20 pounds per square foot disc area. On present-day aircraft, activity factors as high as 140 are not unusual (obtained in some cases by trailing-edge extensions giving unusual blade profiles) and thrust loadings of the order of 70 pounds per square foot are in use.

It might be anticipated that these factors would sufficiently influence the variation of thrust with airspeed, or the increased slipstream velocities would so affect the airplane drag and lift characteristics during the ground run, that a significant variation from Diehl's assumption would be encountered. It therefore appeared appropriate to make use of data obtained from take-off ground-run tests on a number of propeller installations representative of present-day practice and to compare the results with computations based on the original simplified assumption. Also, since the airplane on which the tests were run was one on which considerable wind-tunnel data were available, both with propeller operating and in the presence of a ground plane, it was possible to determine accurately the drag and lift characteristics in the take-off run and to use these characteristics in a more refined method of take-off calculations.

This report presents the experimentally determined take-off ground run of the test airplane equipped with seven different propeller-engine gear-ratio combinations and compares these characteristics with those which would be computed by Diehl's method and by a more detailed method developed herein.

SYMBOLS

a acceleration, foot per second per second

C_D airplane drag coefficient

C_L airplane lift coefficient

d propeller diameter, feet

D drag of airplane, pounds

g acceleration of gravity, feet per second per second (32.2)

L lift of airplane, pounds

m mass of airplane, slugs

μ coefficient of friction (0.03)

q dynamic pressure, pounds per square foot ($\frac{1}{2}\rho V^2$)

R net wheel load

s ground-run distance, feet

S wing area, square feet

T propeller thrust, pounds

T_c thrust coefficient ($T/\rho V^2 d^2$)

W airplane weight, pounds

X forces acting in X direction

Z forces acting in Z direction

EQUIPMENT

The airplane used in the flight tests was a two-place, inverted-gull-wing dive bomber powered by a 2300 brake horsepower air-cooled radial engine. Figure 1 is a drawing of the airplane showing its general arrangement while figure 2 is a front view. Further description may be found in the appendix.

The aerodynamic characteristics of the various four-blade test propellers are as follows:

Propeller	Activity factor per blade	Thickness ratio, 75-percent radius	Diameter (ft)
A	103	0.075	12.67
B	97	.064	13.5
C	106	.076	13.67
D	134	.079	11.17
E	114	.057	13.5
F	122	.055	13.0

Figure 3 is a photograph of the templates of each blade at three-quarter blade radius. It is seen from this figure that the blade of propeller E has been modified by extending the upper camber sheet about two inches beyond the original trailing edge, thus making all the airfoil sections of the blade flapped sections of about 20° flap deflection. Blade F has been modified by extending the lower camber sheet about two inches with no resulting flap deflection.

TEST PROCEDURE

The relative take-off ground runs of the various propeller combinations were compared on the basis of the variation of airplane velocity with ground run. No effort was made to determine the take-off distance, that is, the distance in which the airplane becomes air-borne, since this characteristic is subject to considerable variation depending on pilot technique. Thus the effect, if any, of the various propellers on the "air-borne" speed was not determined in these tests.

To make the various ground runs directly comparable a standard procedure was adopted. Full power was applied with the airplane at a standstill. Brakes were then released, and the entire run up to well beyond the minimum possible take-off speed was made in the three-point attitude. The distance traversed and instantaneous velocity were determined from a motion-picture record of ground markers at 10-foot intervals on the runway. A typical plot of the ground run obtained by this method is shown in figure 4. All runs were made with wind velocities of 3 miles per hour or less and a correction for wind velocity was applied in accordance with the method of reference 1.

COMPUTATION METHODS

A rigorous equation for computing the ground run of an airplane can be developed as follows:

If the summation of forces along the Z-axis (fig. 5) is made then

$$\Sigma Z = 0 = L - W + R \tag{1}$$

or

$$R = W - L \tag{2}$$

Considering the forces acting along the X-axis and neglecting the forces required to accelerate wheel rotation

$$\Sigma X = 0 = T - D - \frac{W}{g} a - \mu R \tag{3}$$

where from Newton's second law of motion $\frac{W}{g}a$ is equivalent to the accelerating force (i.e., net thrust). Substituting the equivalent value of equation (2) into (3)

$$T - D - \frac{W}{g} a - \mu(W - L) = 0 \tag{4}$$

Since the acceleration a may be expressed as

$$a = V \frac{dV}{ds} \tag{5}$$

we have

$$\frac{W}{g} V \frac{dV}{ds} = T - D - \mu(W - L) \tag{6}$$

or

$$ds = \frac{W}{g} \frac{V dV}{T - D - \mu(W - L)} \tag{7}$$

Integrating

$$\int_0^s ds = \int_0^V \frac{W}{g}\,\frac{VdV}{T - D - \mu(W - L)} \qquad (8)$$

or

$$s = \int_0^V \frac{W}{g}\,\frac{VdV}{T - C_DqS - \mu(W - C_LqS)} \qquad (9)$$

By plotting the integrand of equation (9) as a function of velocity and integrating the resultant curve at velocity increments, the desired curve of ground run versus velocity may be obtained. It must be pointed out that both the drag and lift coefficients are functions of thrust coefficient which varies with velocity; hence the values of C_D and C_L must be determined independently at each velocity before being placed in the integrand and used in the integration process. The variables which must be dealt with in equation (9) to determine the net thrust are T, C_D, and C_L. The approximation of the Diehl method assumes that the net thrust varies linearly from static condition to the take-off condition. In contrast, the "refined method" calls for the point-by-point evaluation of T, C_D, and C_L in order to determine the variation of net thrust with velocity.

For the purpose of the present report the charts of reference 2 were used to establish the propeller thrust required by both methods. Tip compressibility losses were accounted for by a method essentially the same as that outlined in reference 3.

In order to evaluate C_D and C_L for the computation of net thrust by the more refined method, wind-tunnel data on the test airplane in the Ames 40- by 80-foot tunnel and 7- by 10-foot tunnel were used. In the former, the lift and drag coefficient variation with propeller operating were determined, and in the latter the additional effect of the ground was evaluated. By the use of these data the variation of C_D with T_c and C_L with T_c, shown on figure 6, for the test airplane in the take-off attitude, with flaps and gear down, was determined. Those values were used in the computation of net thrust by the more detailed method.

RESULTS AND DISCUSSION

Figure 7 shows the comparison between the test data and the results of two methods of calculation. The comparisons for each propeller-engine gear-ratio combination are presented at three engine powers: normal rated (2100 bhp), military (2250 bhp), and take-off (2300 bhp).

It is seen on figure 7 that the calculated ground-run curves correlate with the test curves throughout the speed range presented. Quantitatively the curves check very well except for figures 7(e) and 7(g). The reason for the discrepancy in the data in these figures is most likely due to the incorrect determination of propeller thrust. Because of the relatively small propeller diameter and low propeller rotational speed, the blade angle at 75-percent radius for the propeller D of figure 7(e) is in the neighborhood of 35°. With the blade at this high an angle, it is to be expected that much of the blade will be stalled throughout the ground run, making it difficult to evaluate the thrust correctly. In the case of propeller E (fig. 7(g)), which has deflected-flap sections, it is likely that the use of the charts of reference 2 may lead to an erroneous value of thrust since these charts are based on unflapped blade sections.

A comparison of the calculated curves of ground run (fig. 7(a) to 7(g)) by the two different methods shows the correlation to be very good. The reason for this may be explained by the comparison of the net thrusts (i.e., the thrust available for acceleration) as shown on figures 8(a) to 8(g). It is seen that the net thrust as determined by Diehl's method (estimating the thrust at the static condition and the "lift off" point and drawing a straight line between) checks the values determined by the refined method with an excellent degree of accuracy. A reasonable explanation for this accuracy requires a further study of the basic variables involved.

Diehl, in arriving at his assumption of linear variation of net thrust, considered the facts that (1) at a constant angle of attack the aerodynamic drag will vary as the square of the airspeed, (2) the friction drag will vary as the wheel load (neglecting slipstream effects), and (3) the thrust will vary with a substantially linear relation with airspeed. Examining just the drag coefficient and its variation on figure 9(a), it is seen that at the low-speed range of the take-off run an appreciable deviation exists between the power-on value of drag coefficient and the constant value assumed by Diehl in developing his method. This deviation yields an aerodynamic drag force that is about 1000 pounds greater than that obtained by using the power-off value of drag coefficient (fig. 9(b)). This result leads one to inspect the lift variation between the two methods, since wheel friction force is dependent upon lift.

Figure 10(a) shows the variation between the power-on values of lift coefficient and the value as used to determine the variation of wheel friction force with airspeed for Diehl's method. It is again seen that a wide deviation exists at the low-speed range of the run. (The speed range of from 66 ft/sec to 124 ft/sec corresponds to the speed range for which the take-off runs are presented on figure 7, i.e., 45 to 85 mph.) Even though the difference in lift coefficient used in the two methods is about $\Delta C_L \cong 1.0$, the wheel friction drag difference is very slight (fig. 10(b)). The reason for this slight difference is because the wheel drag is the product of the coefficient of friction $(\mu = 0.03)$ and the difference between the airplane weight and lift. Since the wheel friction drag difference is only 100 pounds and the aerodynamic drag difference is about 1000 pounds, one would expect the net thrusts to be off by about 900 pounds and yet the maximum net thrust deviation of figure 8(a) to 8(g) was only 300 pounds. Figure 11 gives a reasonable explanation for the close agreement of net thrusts as determined by the two methods. The propeller of figure 8(a) is used as an illustrative example. Curve (a) of this figure shows the variation of total airplane drag as determined by adding the aerodynamic and friction drags used in Diehl's original consideration of the problem. When the total drag as used in the refined method is compared with Diehl's, it is seen that a very wide discrepancy may be disregarded since the variation as determined by the refined method approximates more closely the linear variation (curve (b)) resulting from Diehl's final assumption of a linear net thrust variation. It may then be concluded that for an airplane on which the slipstream effects are sizable a linear variation of total drag is more closely approximated than for an airplane on which the slipstream effects are negligible.

Figure 12 is a summary figure of the individual propellers. It shows a comparison between the calculated and experimental test distances covered at an airplane speed of 80 miles per hour (approximate take-off speed) for 2250, 2300, and 2100 brake horsepower.

It is seen that the majority of the calculated distances are in error by less than ±7 percent of the test distances except for propellers D (gear ratio = 0.4375) and E at 2300 brake horsepower. The source of error for both of these propellers is most likely that of thrust estimation as has been previously explained. The inability to accurately compute the thrust for these two propellers has directly contributed to the errors in predicted take-off distance. Hence, it may be concluded that, at the present time, the most significant contribution to the more accurate prediction of take-off run will be that of the provision of methods for the more accurate estimation of take-off thrust, particularly in the case of unorthodox propeller designs and of propellers operating under unfavorable power loading conditions.

CONCLUSIONS

From the examination of the data presented herein the following conclusions are drawn:

1. In a majority of cases, values of ground run calculated by Diehl's approximate method checked experimental values within ±7 percent but were in error as much as 10 percent for a propeller with a deflected trailing-edge flap, and 15 percent in the case of a propeller which was operating at an unfavorable power loading.

2. Attempts to improve the accuracy of ground-run calculations by use of a more rigorous method do not appear warranted unless strictly applicable lift, drag, and particularly thrust data are available.

3. Improved methods of thrust computation are required in order to avoid large errors (in unusual cases) in Diehl's method, and before any more rigorous method may profitably be substituted for Diehl's approximate method.

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APPENDIX

A more complete description of the airplane and test equipment is presented below:

Airplane, general

Span, ft.	44.62
Length, ft.	38.56
Weight (as tested), lb.	16,000
Wing	Laminar-flow-type sections with thickness varying from 18 percent at root to 15 percent at tip
Area, sq ft	375

Engine

Type	R-3350

Ratings

	bhp	rpm	Altitude
Take-off	2300	2800	Sea level
Military	2250	2600	2800 ft
Normal	2100	2400	2500 ft

Gear ratio. . . . . 0.4375 or 0.5625 (depending upon installation)

INSTRUMENTATION

Standard NACA instruments were used to record photographically, as a function of time, quantities from which the following variables could be obtained: normal and longitudinal acceleration, manifold pressure, engine speed, engine torque, airspeed, and altitude. An observer measured the wind speed by use of a sensitive velometer.

TESTS

The ground-run tests were conducted with the test airplane at a gross weight of 16,000 pounds. Flaps were deflected 35°, oil-cooler and cowl flaps were fully open. Ground runs were made by alining the airplane at the starting point and applying the specified power conditions. When power conditions were steady, the instruments were turned on by the flight observer and the brakes were released. The airplane was kept on a straight course by use of the rudder alone, and the entire run was made in the three-point attitude.

Tests were conducted at the two different engine-propeller gear-ratio combinations of 0.4375 and 0.5625 because of the large variation in the diameter of the propellers tested. The lower ratio (0.4375) was generally used with the large diameter propellers so that excessive tip speed losses would not be incurred. Thus propeller A was tested at the 0.5625 gear ratio; whereas propellers B, C, E, and F were tested at the 0.4375 gear ratio. Propeller D, however, was tested at both gear ratios. To accommodate the propellers of $13\frac{1}{2}$-foot diameter and larger, the nose-wheel strut of the airplane was extended in such a fashion that the ground-run angle of attack was increased nearly 2°. This factor has been taken into account in the computations.

The ground-run data from the high-speed camera were plotted as distance versus time. This curve was then differentiated to give airplane velocity versus time from which a final curve of ground run versus velocity could be obtained.

REFERENCES

1. Diehl, Walter S.: The Calculation of Take-Off Run. NACA Rep. No. 450, 1932.

2. Desmond, Gerald L., and Freitag, Robert F.: Working Charts for the Computation of Propeller Thrust Throughout the Take-Off Range. NACA ARR No. 3G26, 1943.

3. Thomas, F. M., Caldwell, F. W., and Rhines, T. B.: Practical Airscrew Performance Calculations. Jour. Aero. Sci., vol. 42, no. 325, Jan. 1938, pp. 1-86.

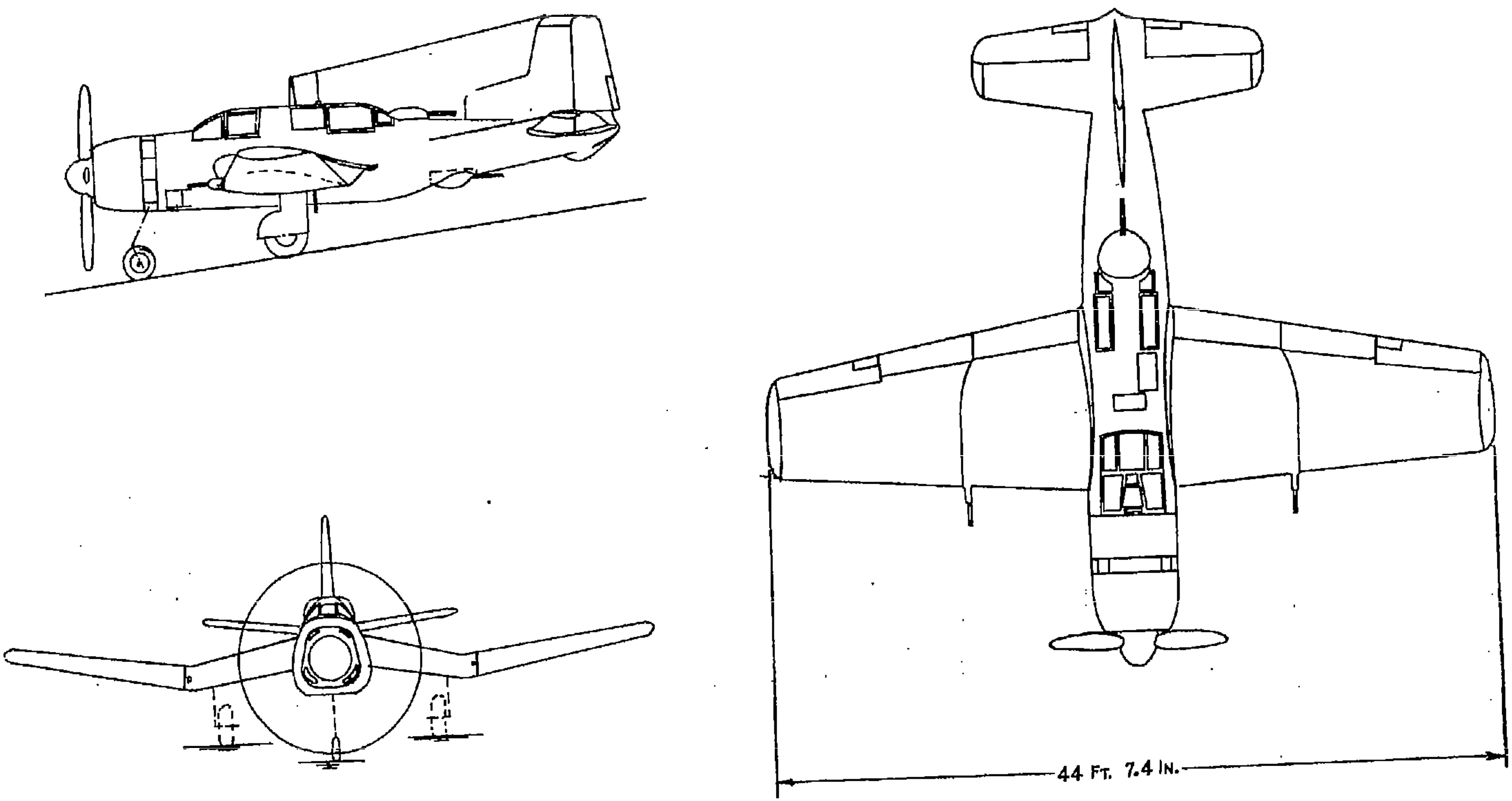

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Figure 1.- Three-view drawing of test airplane.

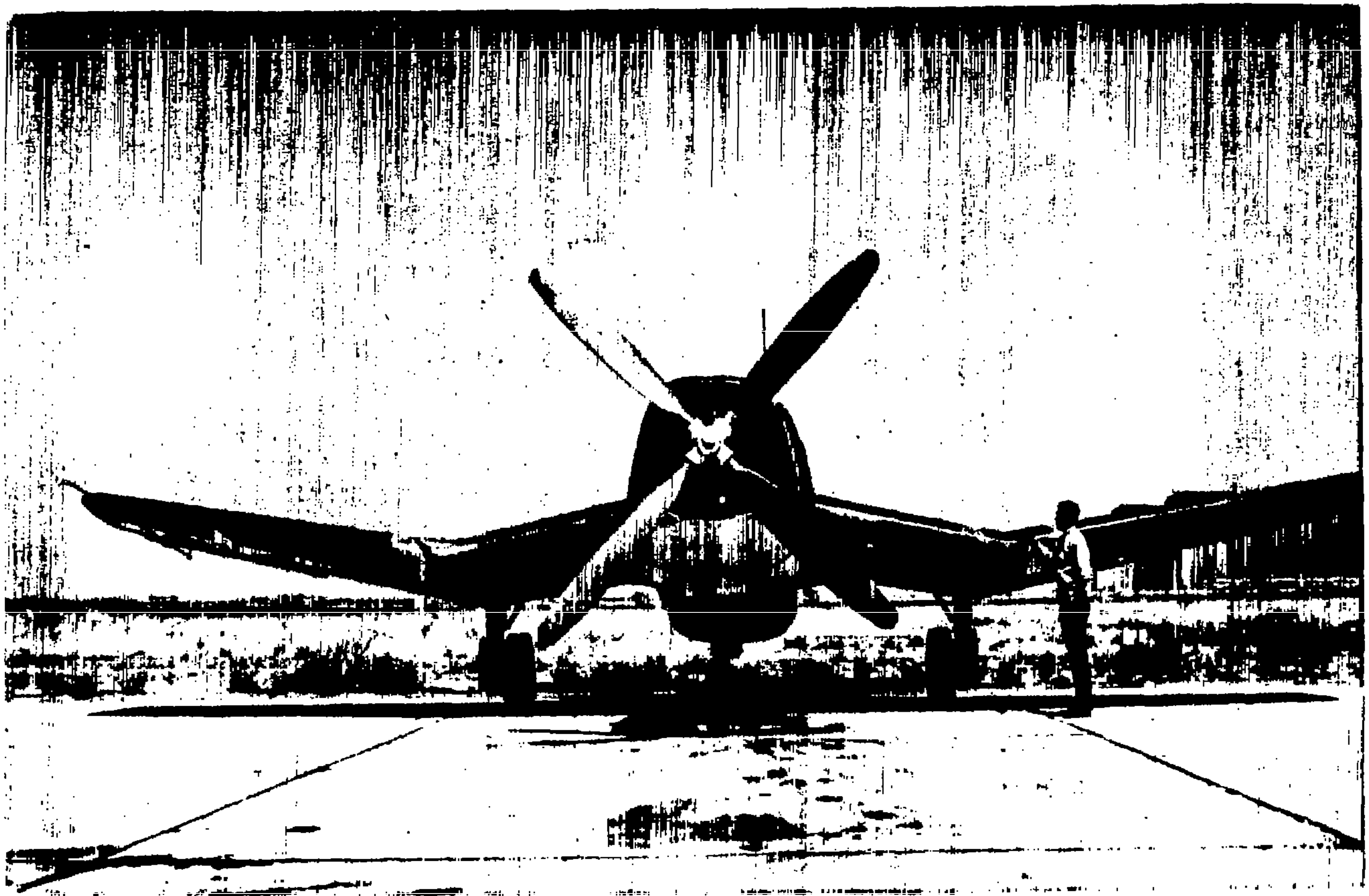

Figure 2.- Front view of test airplane.

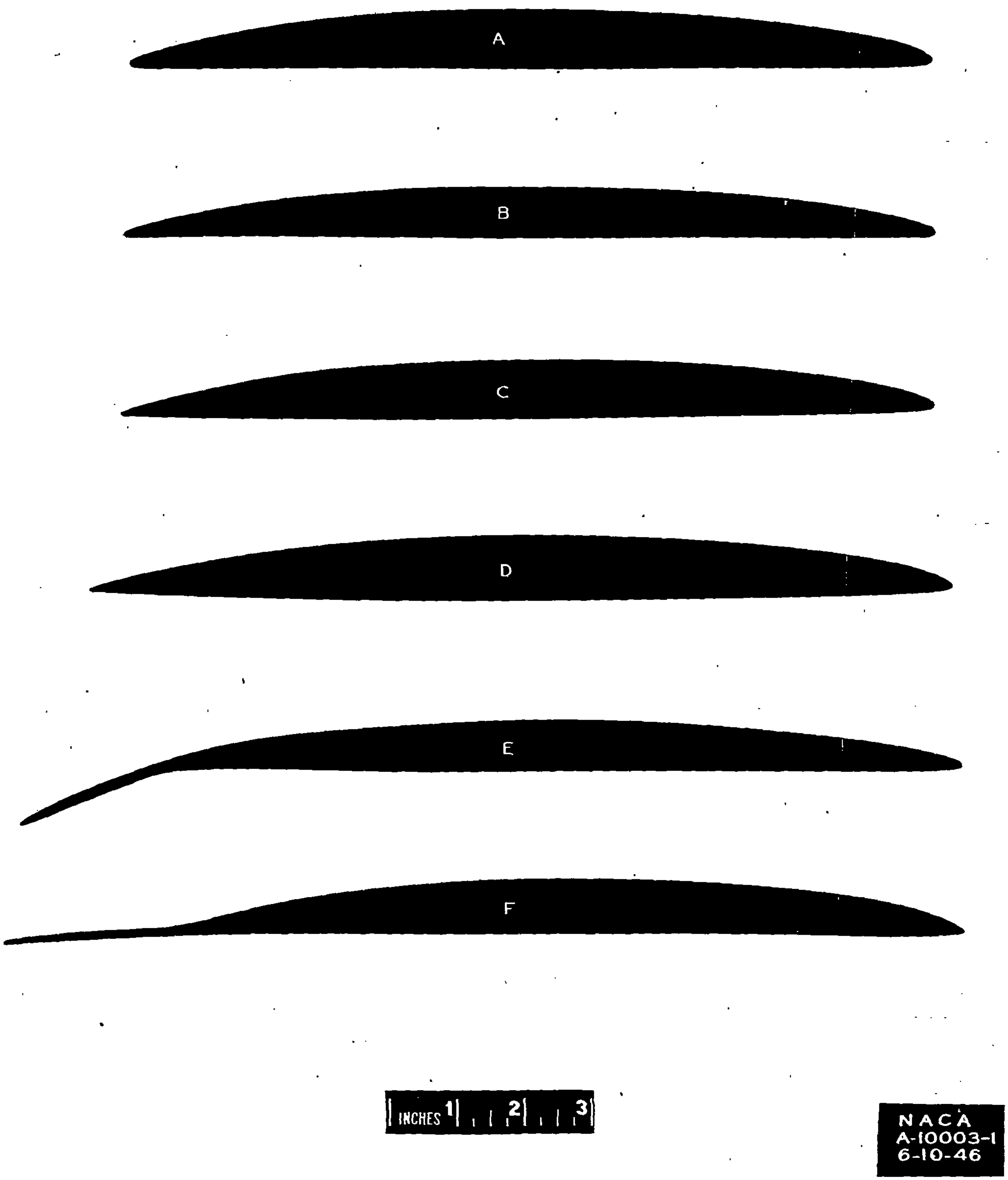

Figure 3.- Blade sections of test propellers at 75-percent radius.

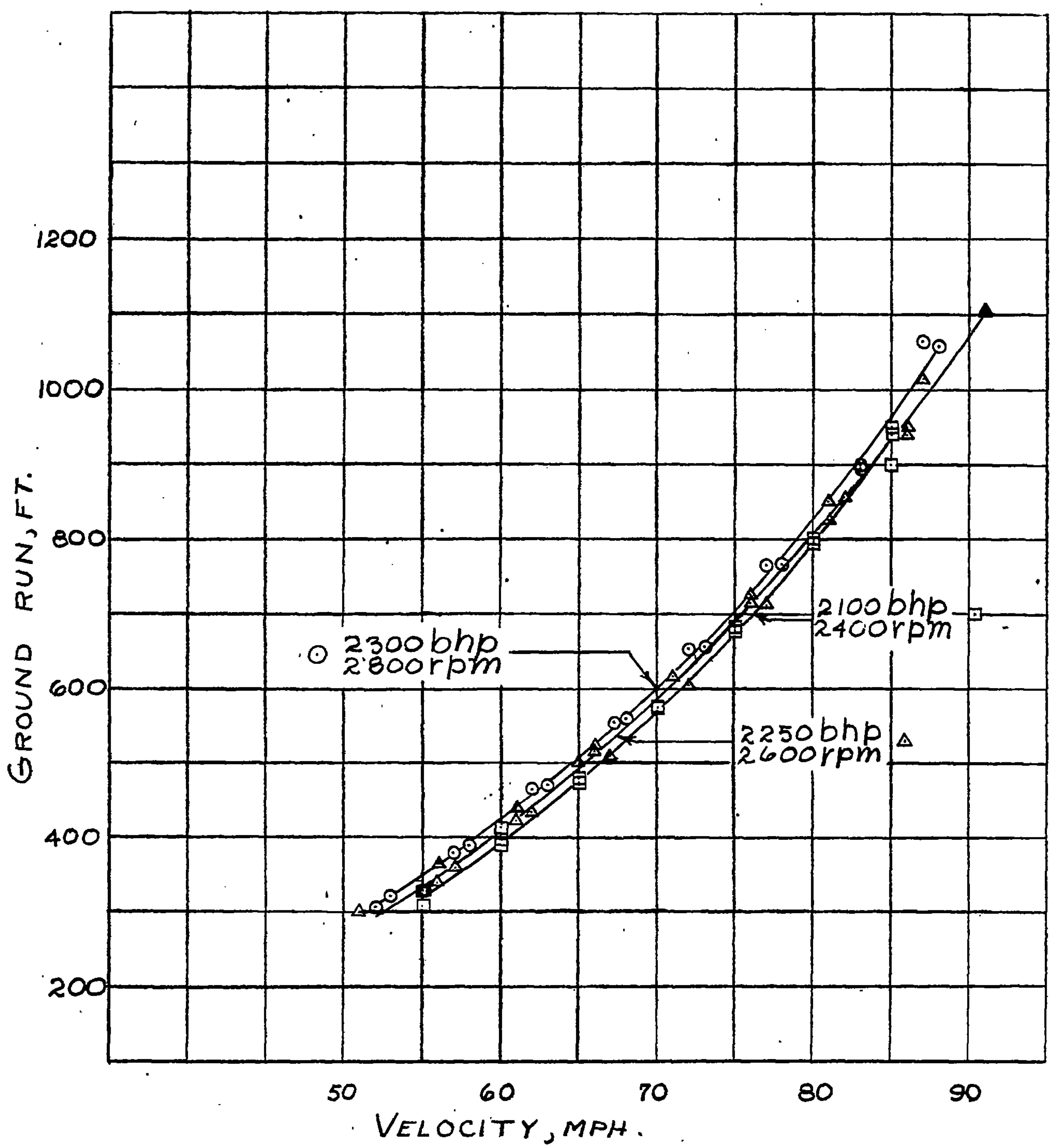

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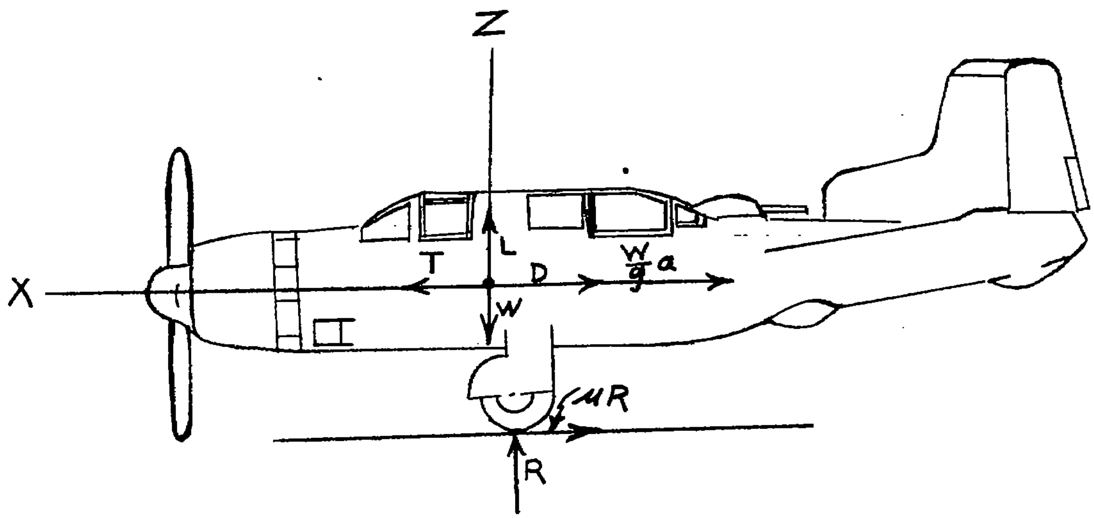
Figure 4.- Typical test data for ground run of airplane with propeller configuration A installed.



WHERE

L = AIRPLANE LIFT

W = AIRPLANE WEIGHT

T = PROPELLER THRUST

D = AERODYNAMIC DRAG

$\frac{W}{g}a$ = INERTIA FORCE

R = NET WHEEL LOAD

μR = GROUND FRICTIONAL FORCE

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Figure 5.— Forces acting on airplane during ground run.

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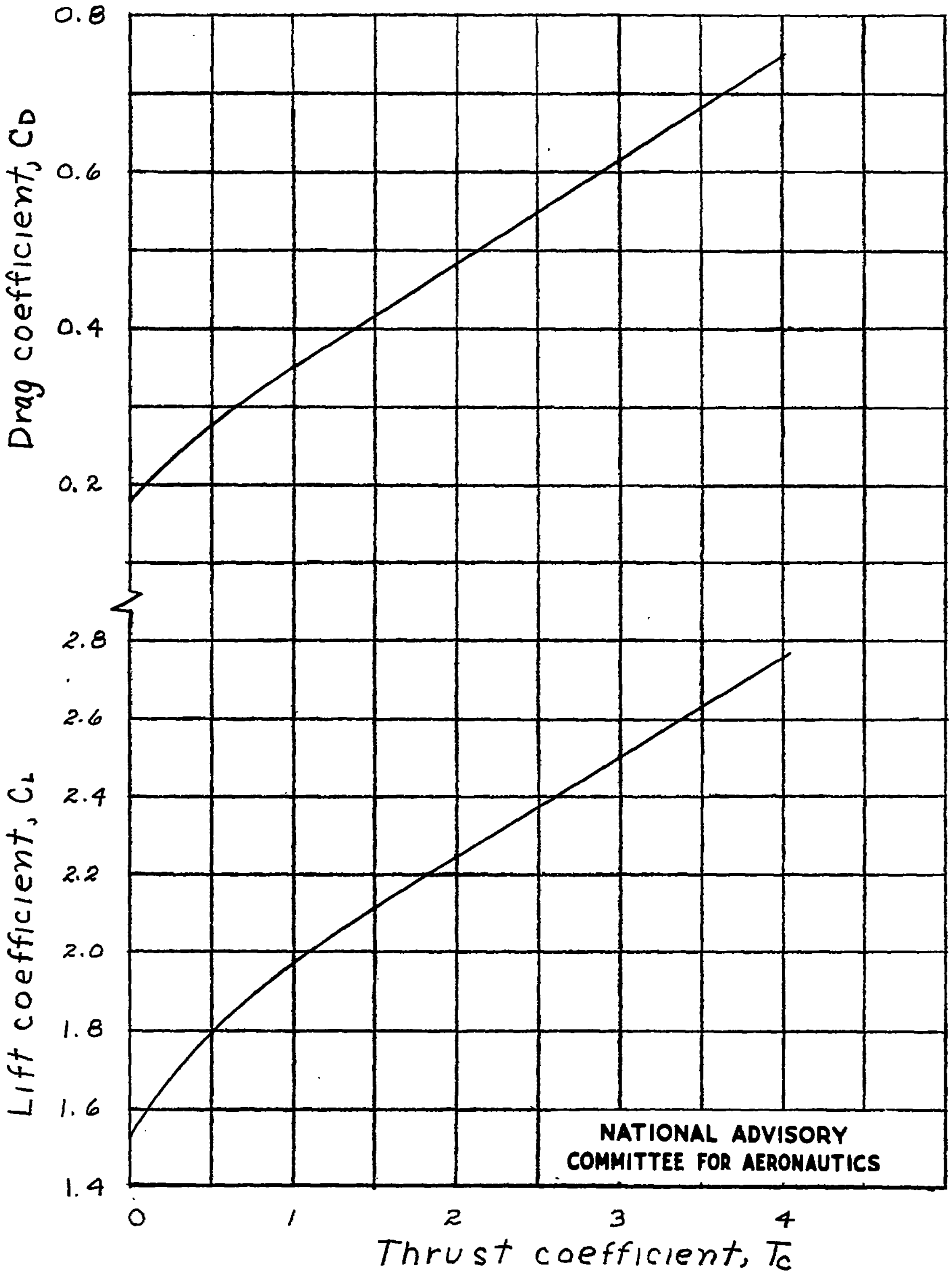
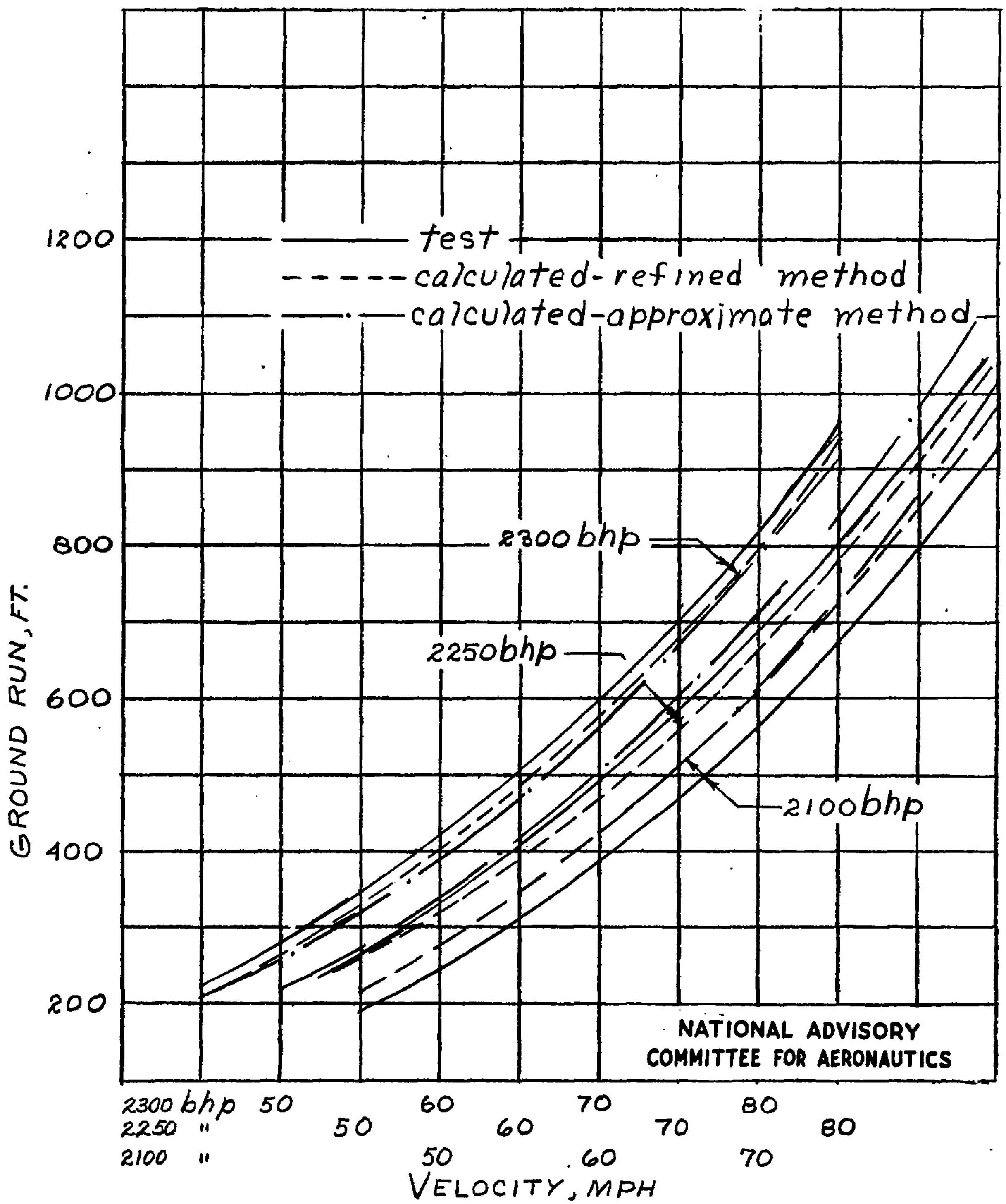
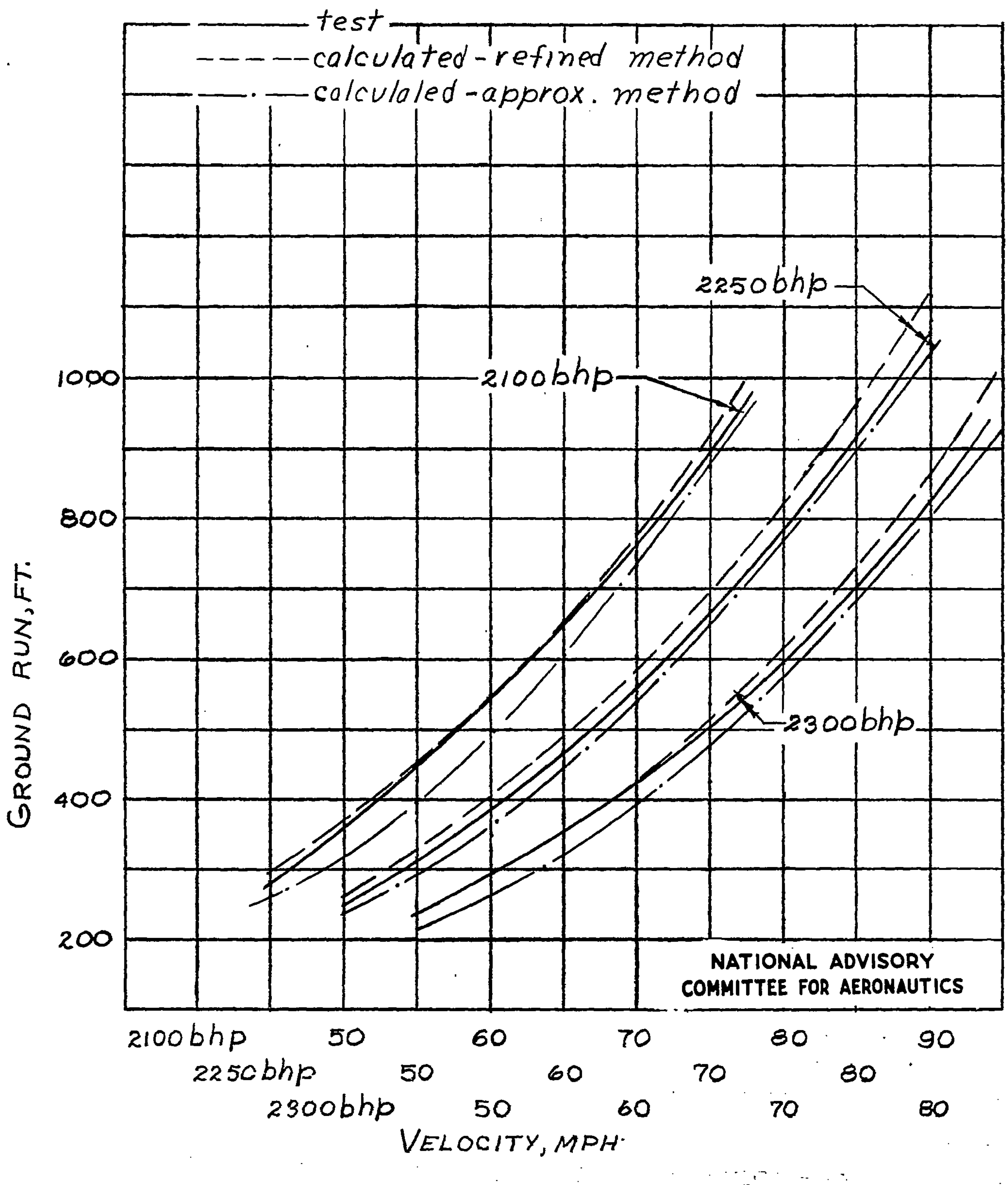


Figure 6.- Variation of lift and drag coefficients with thrust coefficient for the test airplane in the take-off configuration.



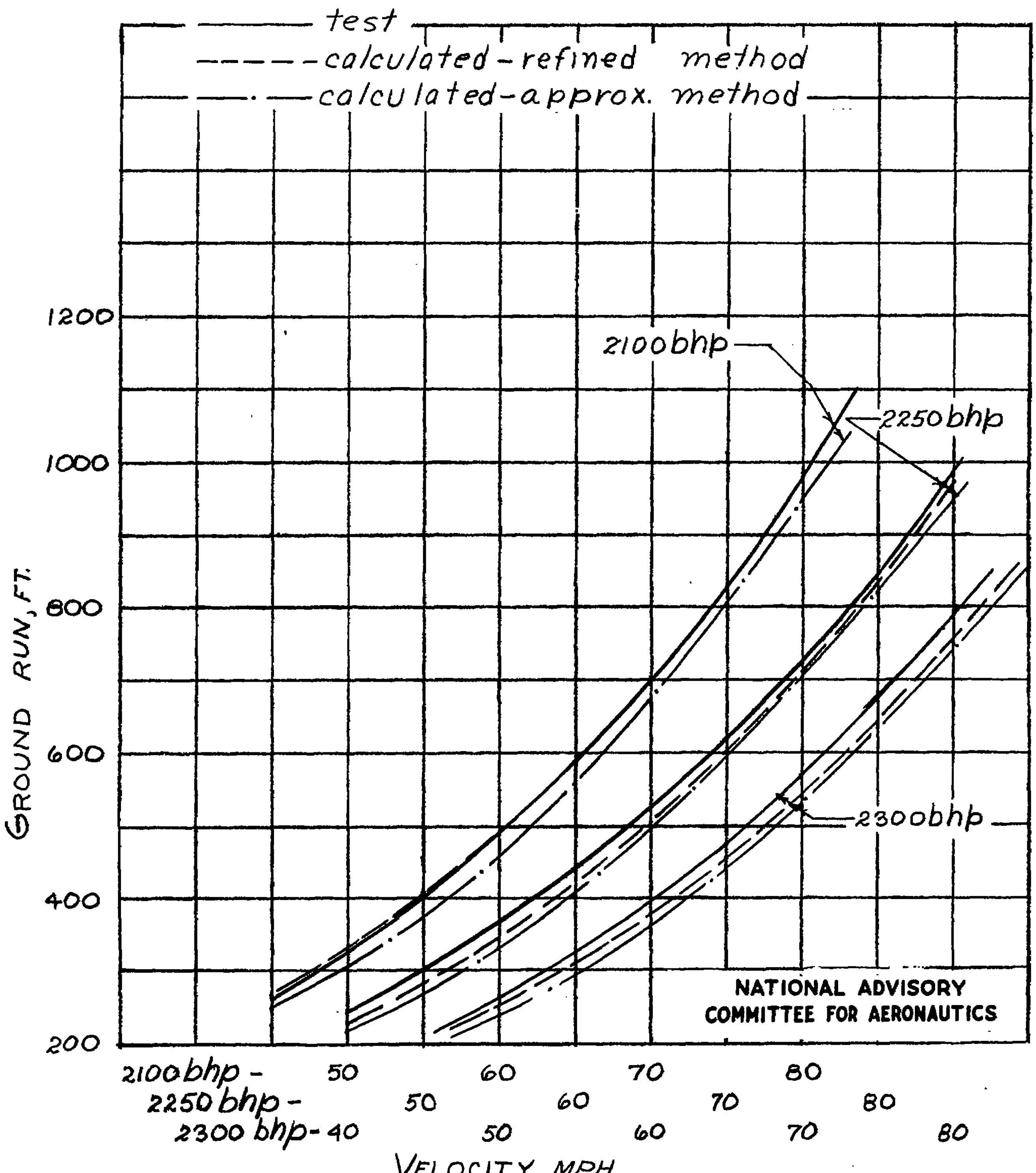
(a) Propeller A at 0.5625 gear ratio

Figure 7.— Variation of ground run with velocity for the airplane as determined by calculation and by test.



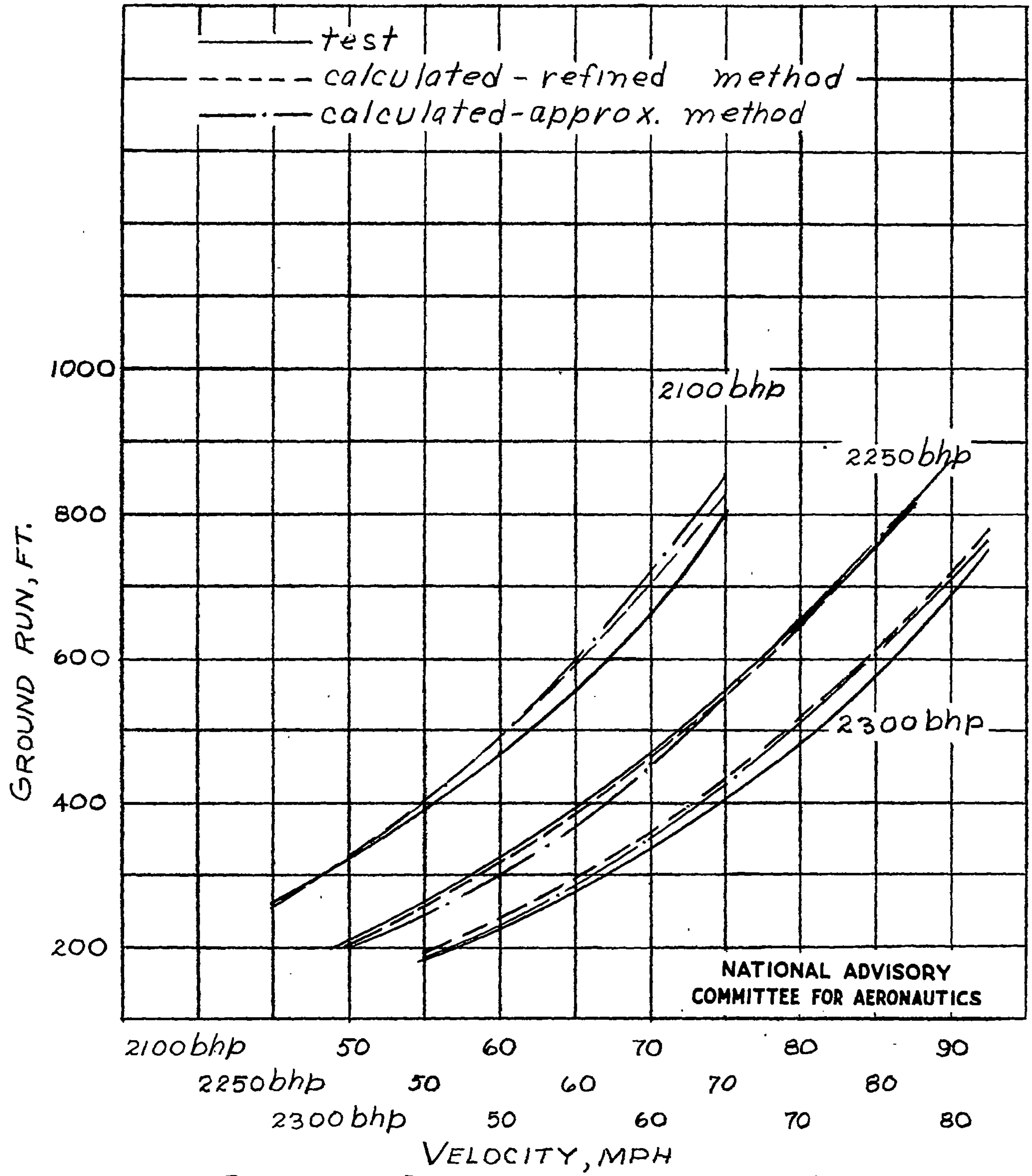
(b) Propeller D at 0.5625 gear ratio.

Figure 7.- Continued



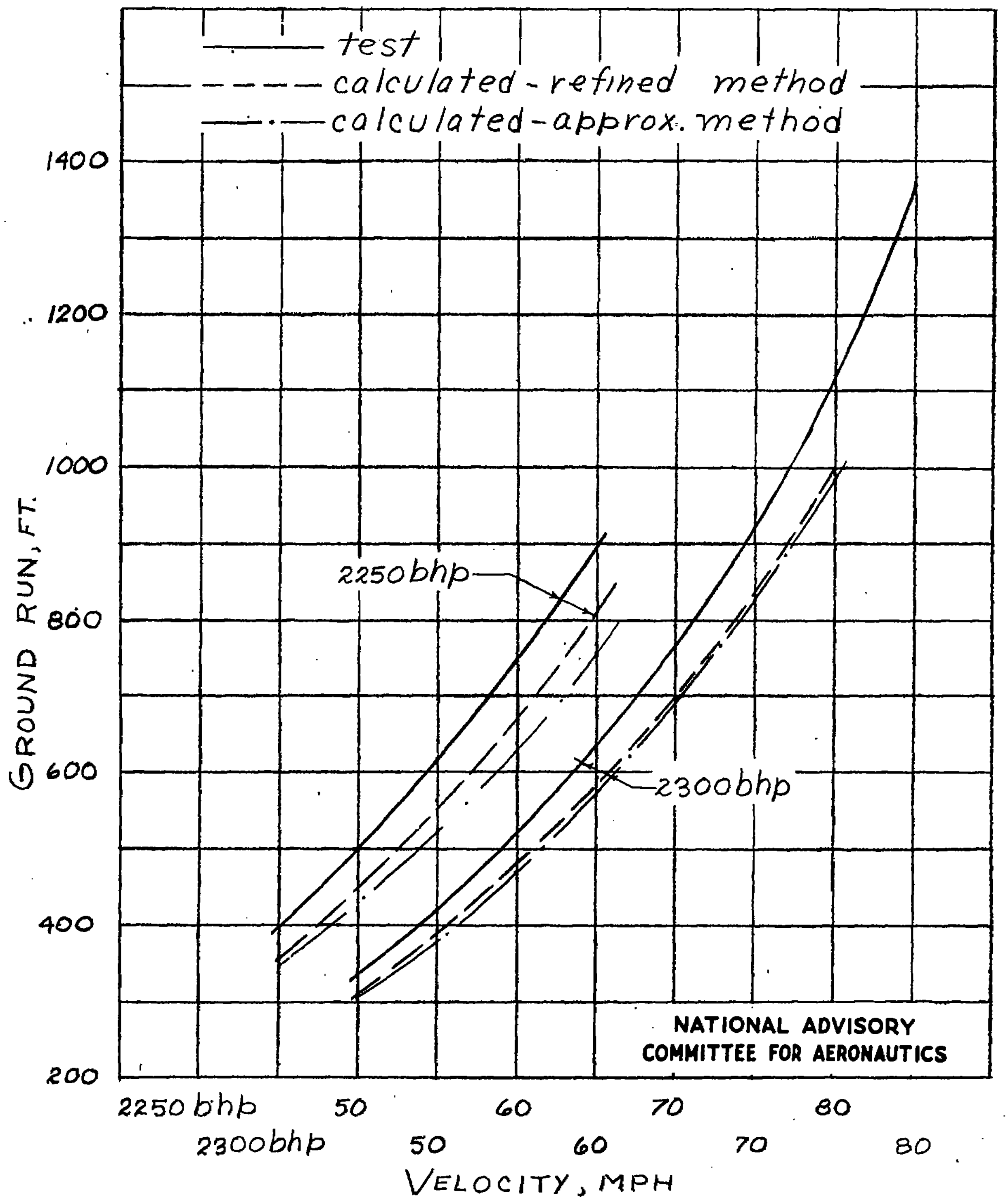
(c) Propeller F at 0.4375 gear ratio

Figure 7. - Continued



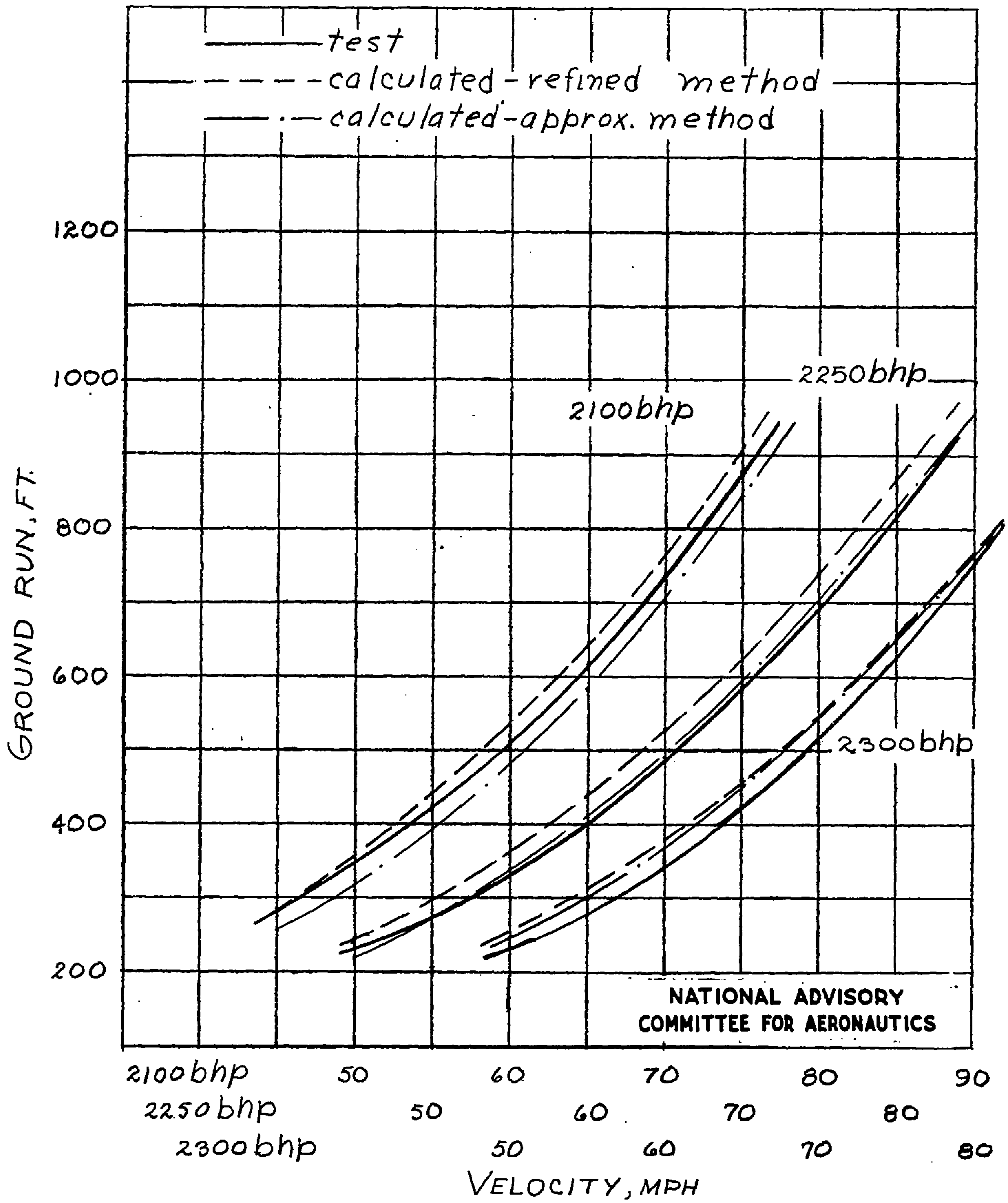
(d) Propeller C at 0.4375 gear ratio

Figure 7.– Continued



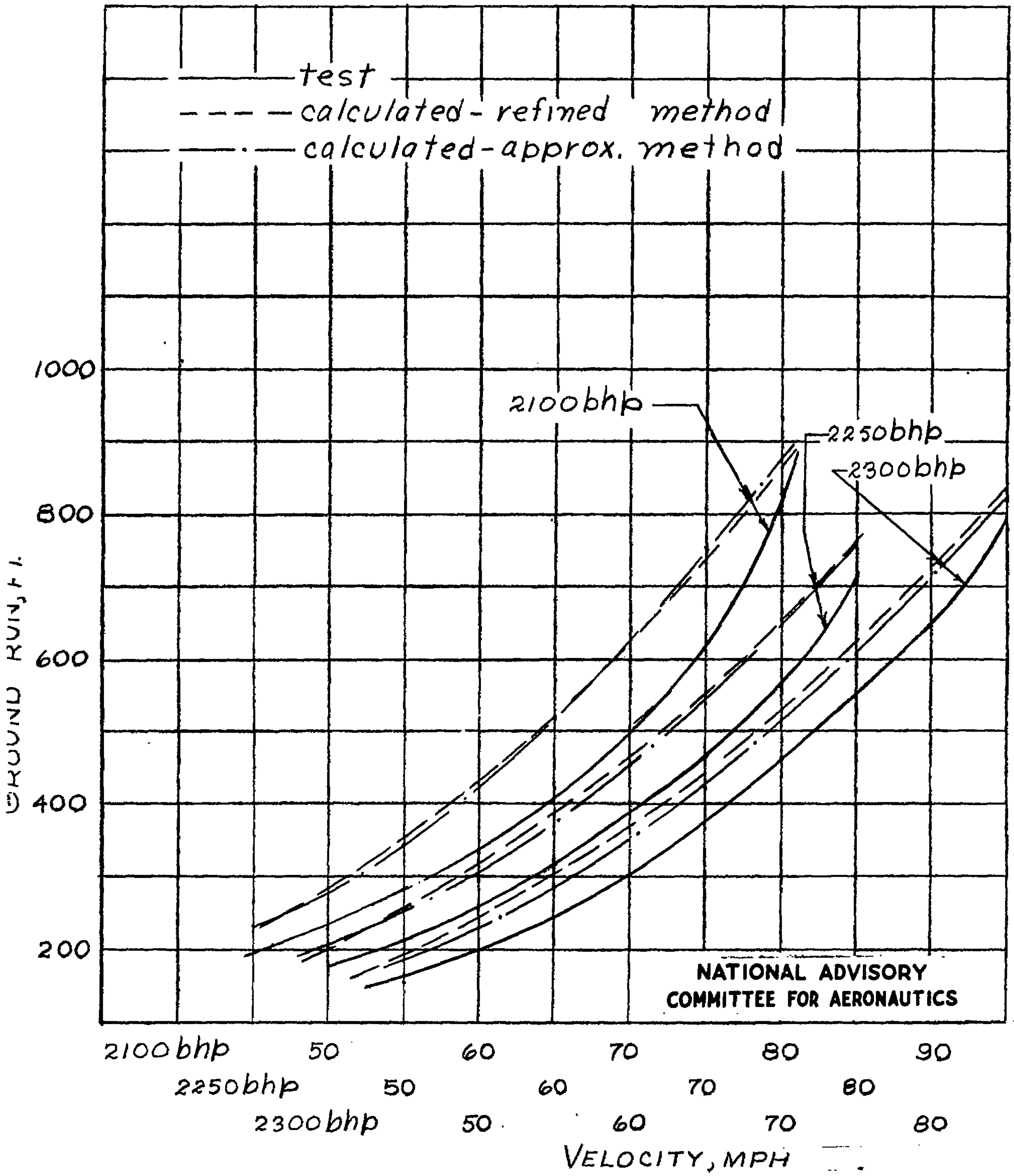
(e) Propeller D at 0.4375 gear ratio

Figure 7.— Continued



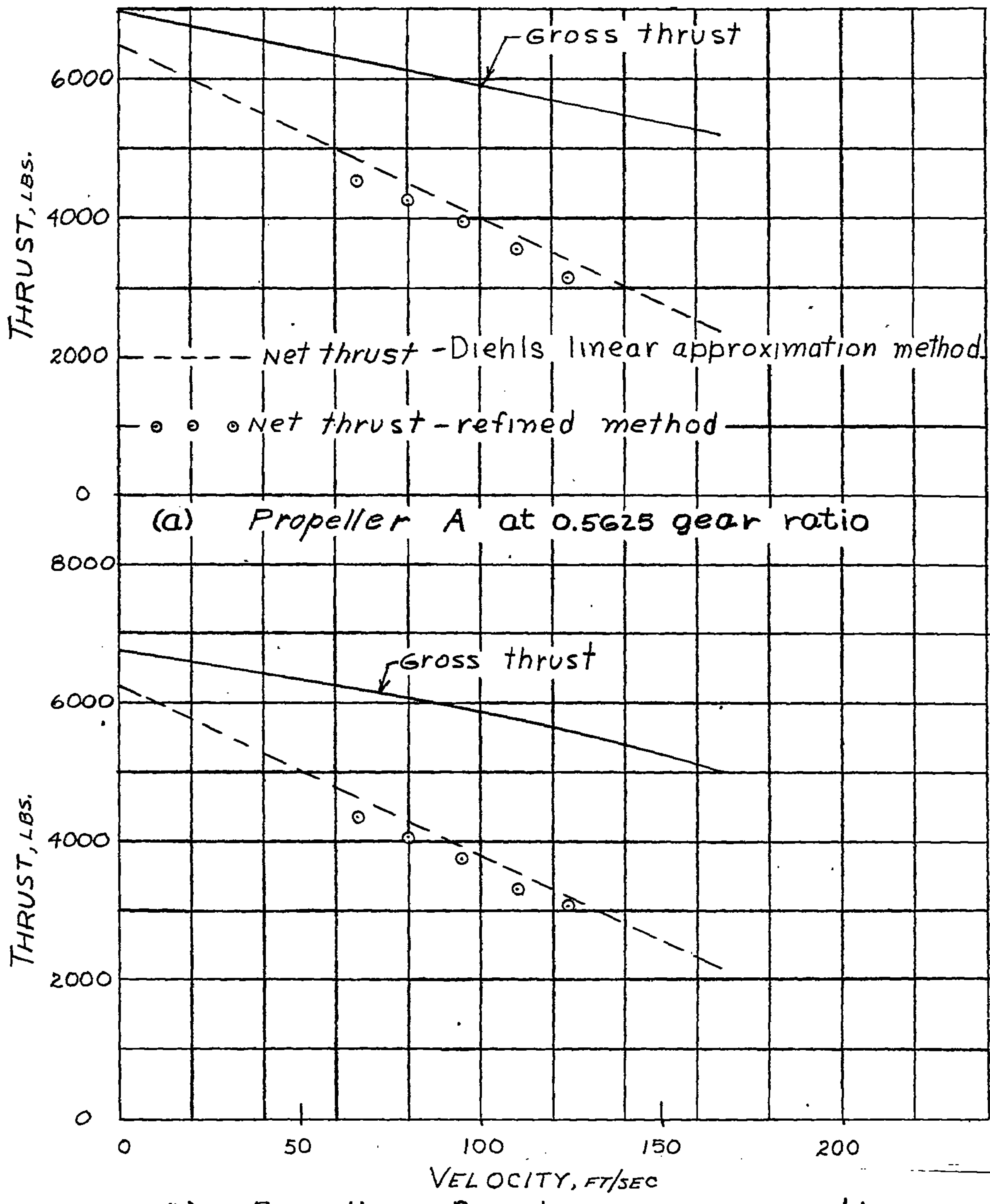
(f) Propeller B at 0.4375 gear ratio

Figure 7.- Continued



(g) Propeller E at 0.4375 gear ratio

Figure 7.– Concluded



(b) Propeller D at 0.5625 gear ratio

Figure 8.— Variation of calculated thrusts with airspeed for the test airplane at take-off power.

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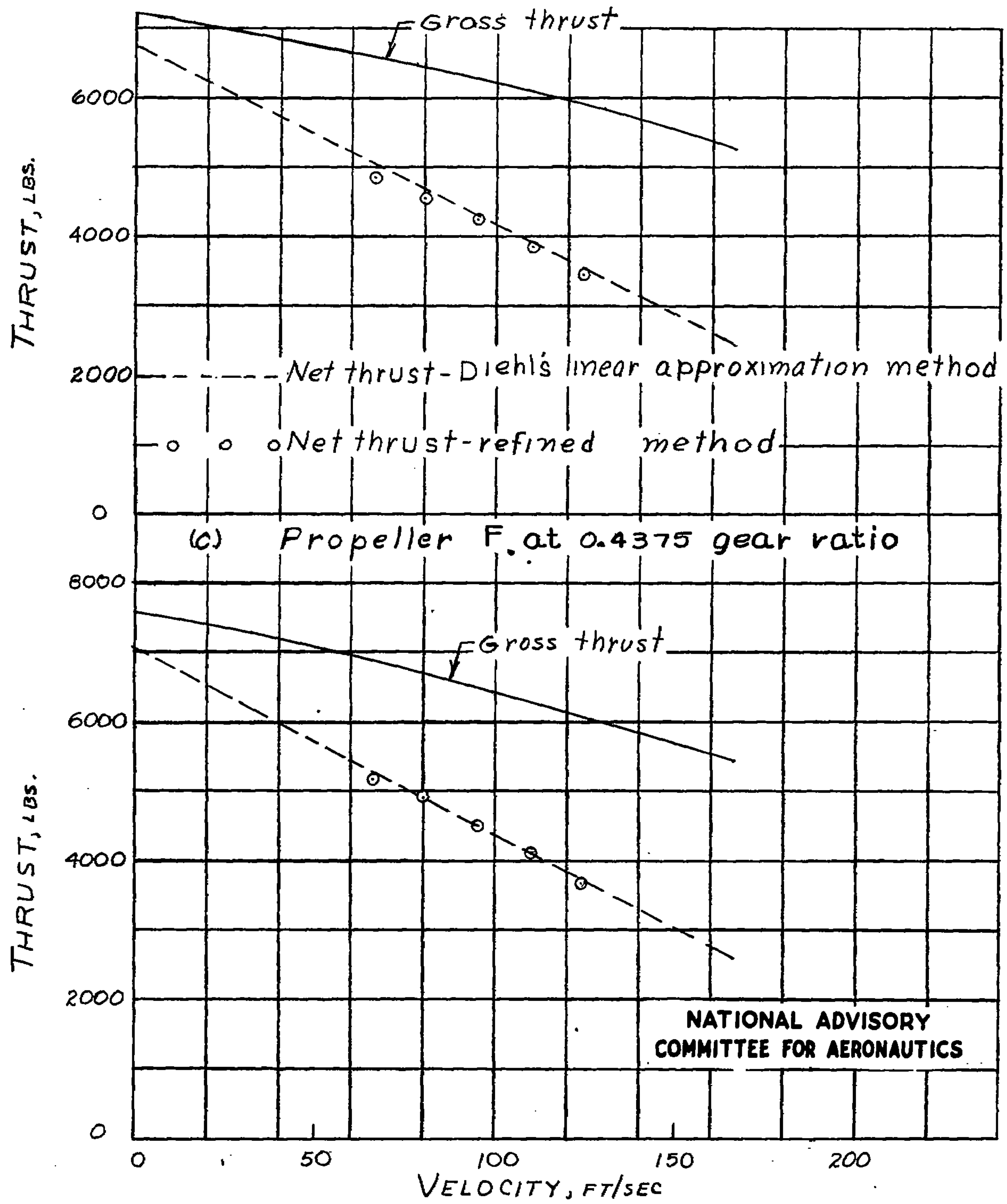
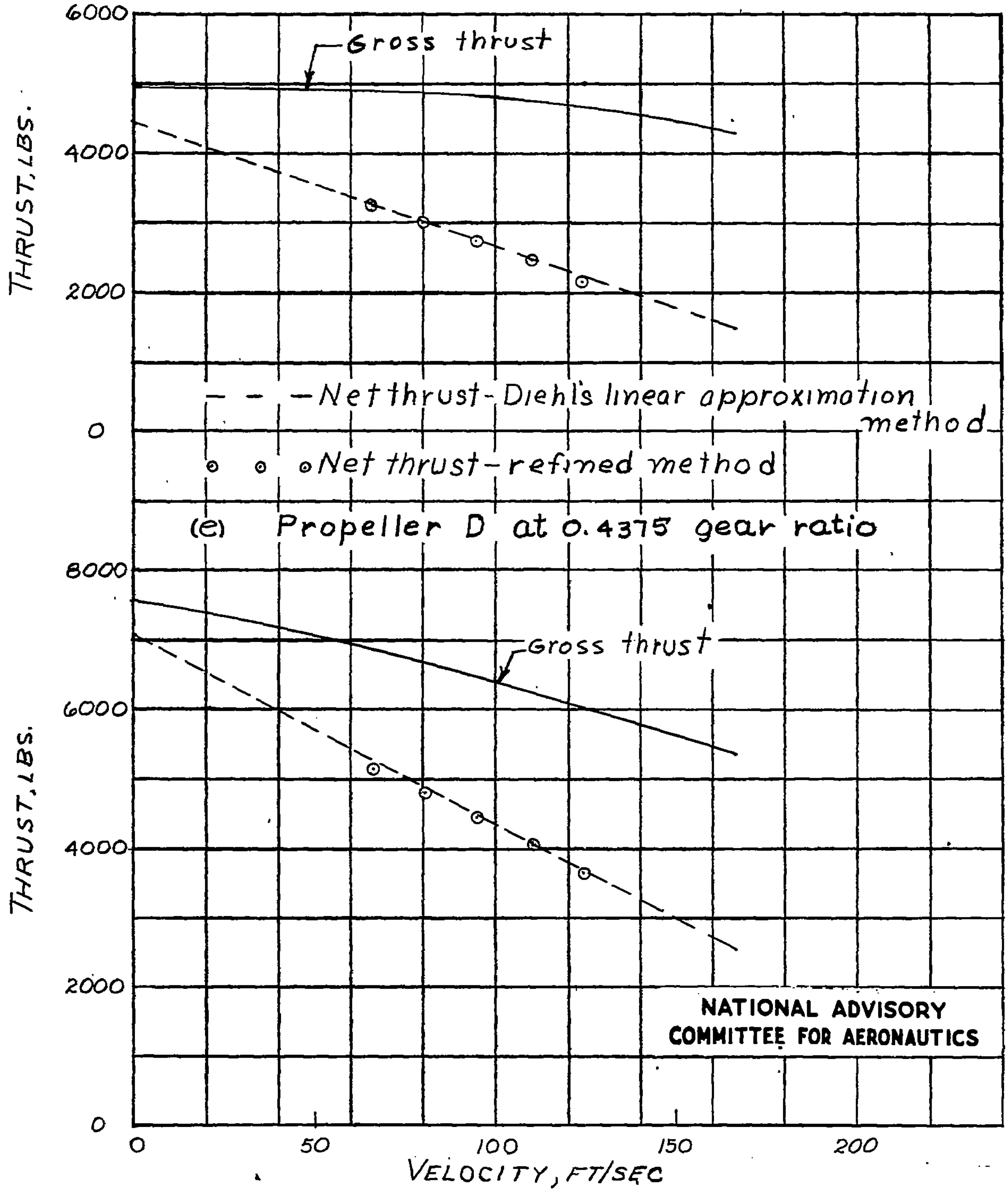


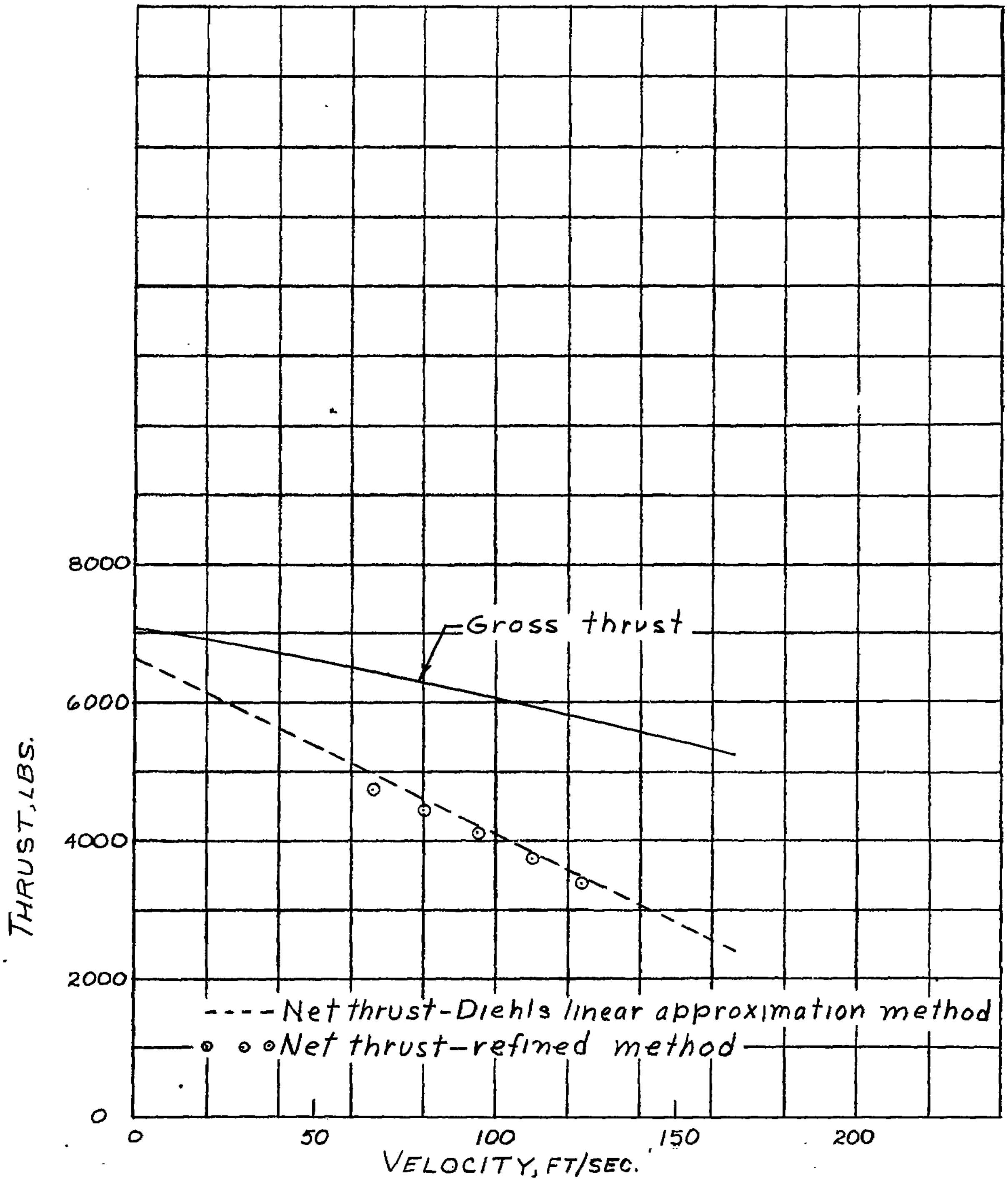
(d) Propeller C at 0.4375 gear ratio

Figure 8.- Continued.



(f) Propeller E at 0.4375 gear ratio

Figure 8.- Continued.



(g) Propeller B at 0.4375 gear ratio
Figure 8.— Concluded.

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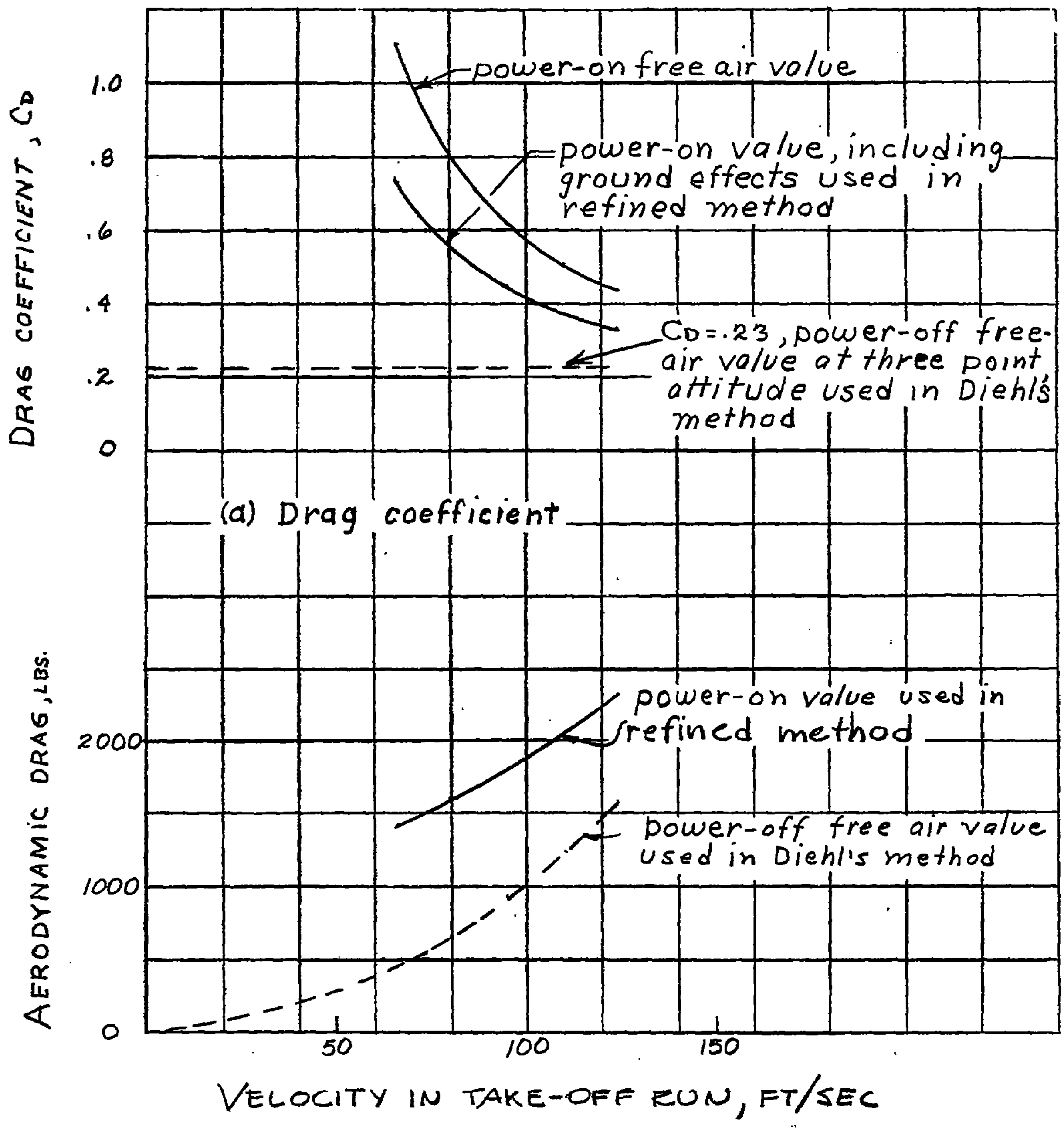

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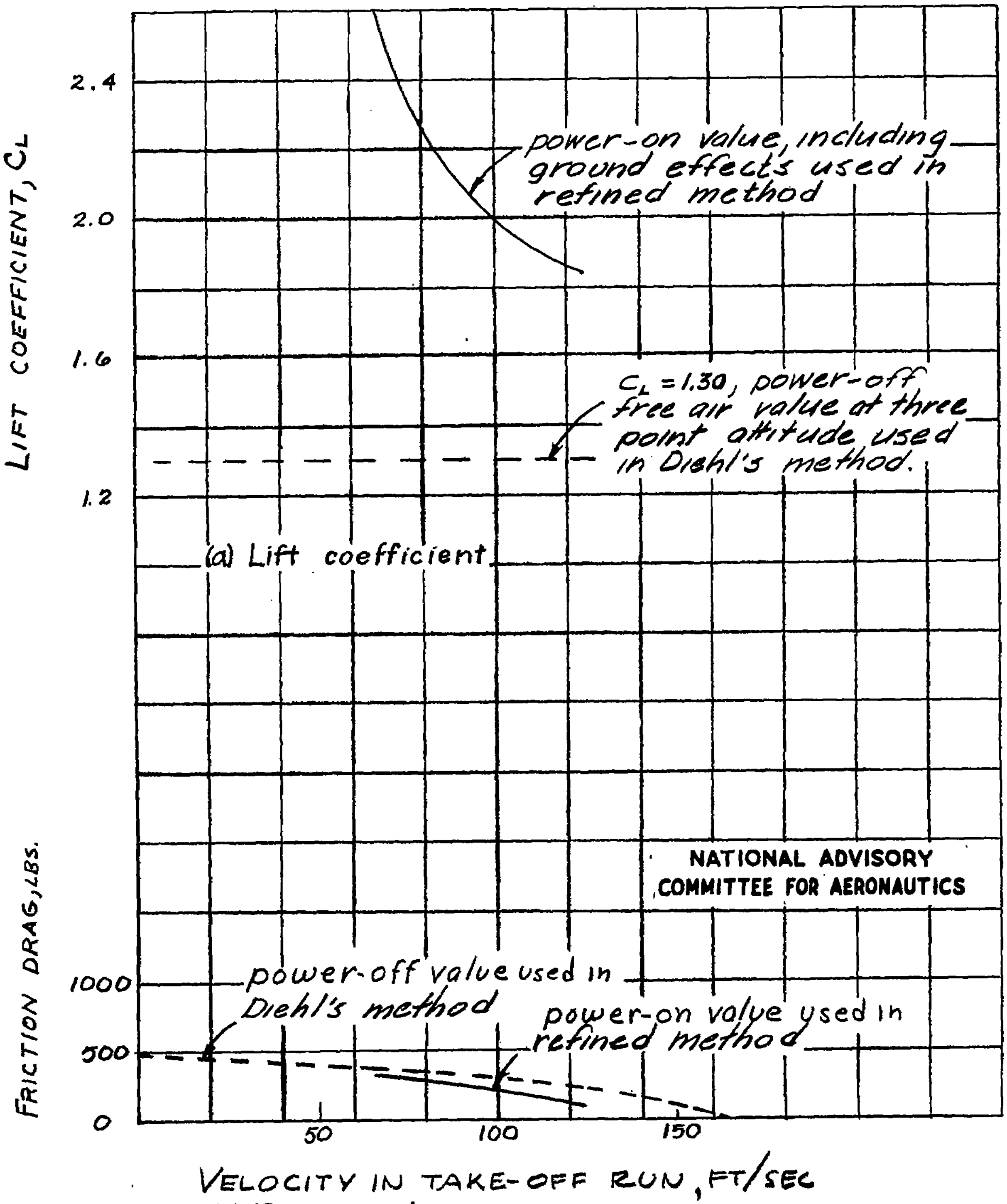
Figure 9.-Variation of drag coefficient and aerodynamic drag with velocity in the take-off run.



(b) Friction drag

Figure 10.– Variation of lift coefficient and wheel friction drag with velocity in the take-off run.

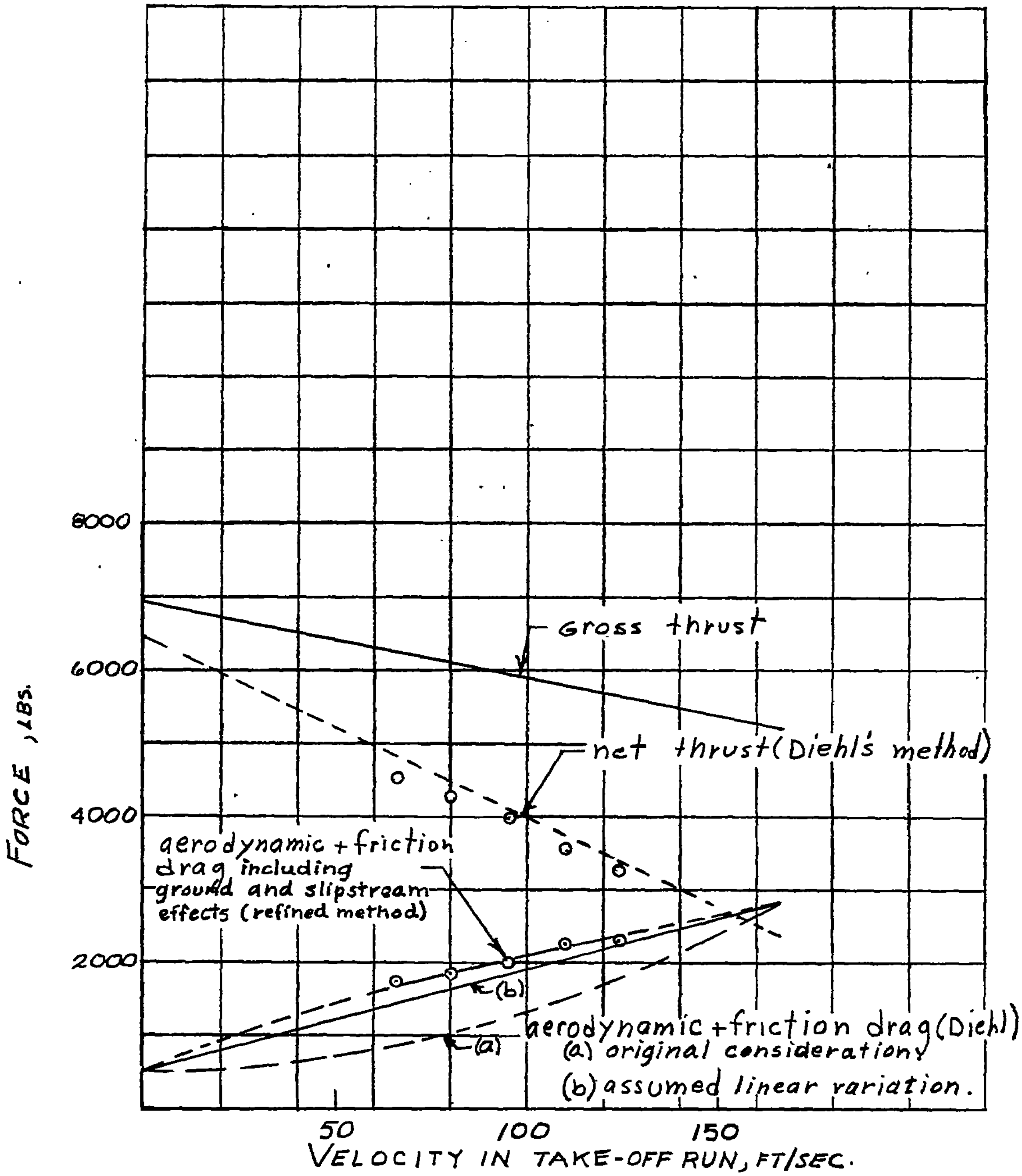


Figure 11.– Major variables acting during the take-off run with propeller A installed.

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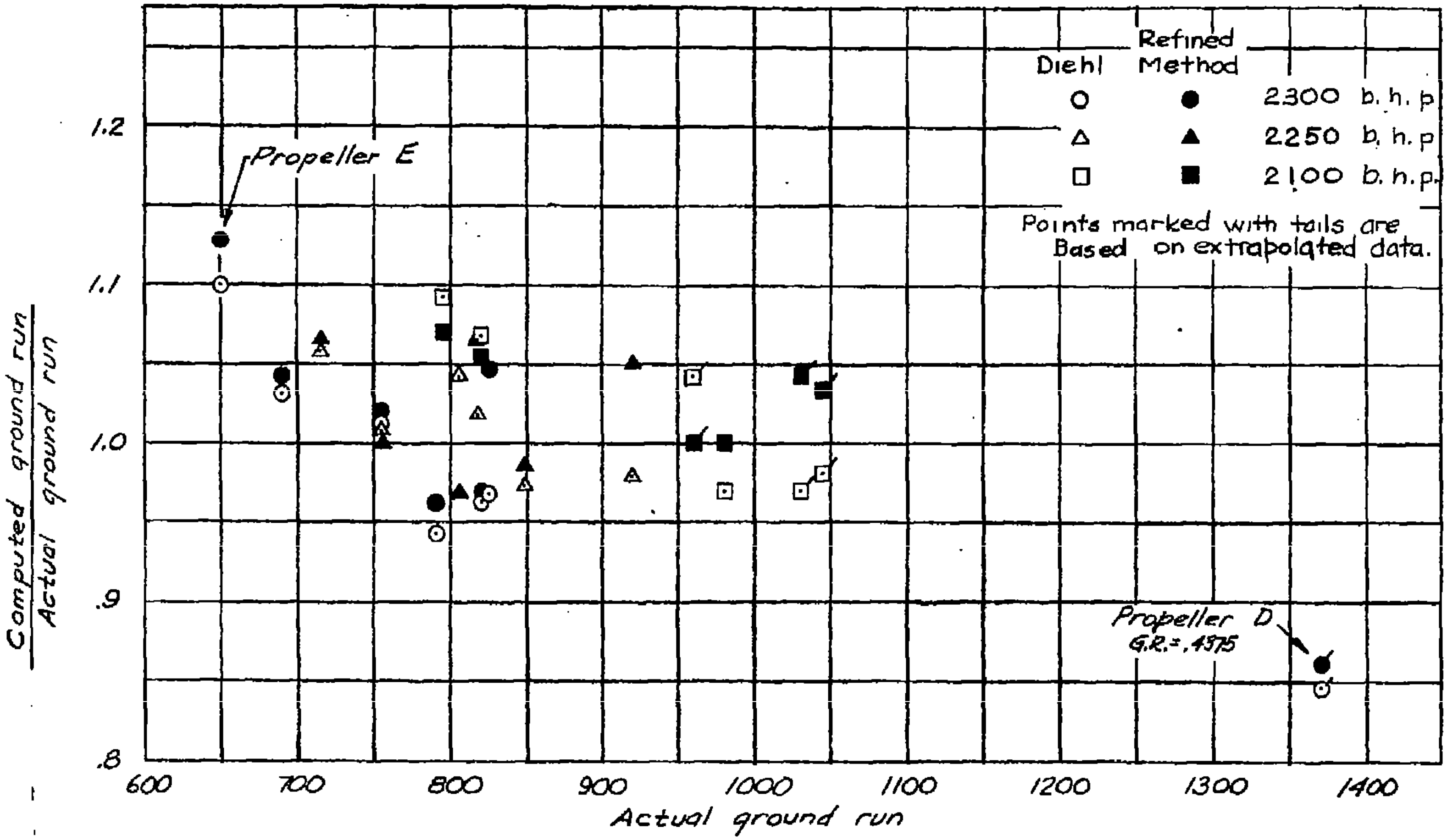

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Figure 12.- Summary chart comparing the computed ground run with actual ground run to reach a take-off speed of 80 miles per hour.

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